4 Findings

This chapter summarizes the major results of work already completed. Most of these results represent analyses carried out by CARB staff. The findings presented here are generally isolated results but are organized by the study objectives. More integrated "conclusions" are presented in the following chapter.

The findings outlined below primarily address the South Coast Air Basin, where ambient ozone concentrations are the highest in the state and the monitoring network is the most extensive in California. Additional air basins in California are included in some findings regarding measurements of ambient air quality on weekdays and weekends.

4.1 Objective #1 – Characterize the weekend effect

Finding #1: The ozone weekend effect has differences and similarities in different areas of California

Analyses of ozone data during the 1990s considered four areas of California – the South Coast Air Basin, the San Francisco Bay Area Air Basin, the Sacramento Metropolitan area, and the San Joaquin Valley. The results reveal the following:

- *The day-of-week effects vary from area to area. The weekend effect is most evident in coastal metropolitan regions (Table 4-1).*

Table 4-1. Weekend effects in four regions – average result for sites in each region based on ozone data for 1996 through 1998.

Region	Sites Used	Friday to Saturday	Saturday to Sunday	Sunday to Monday
South Coast	18	Up 19%	Up 11%	Down 22%
S.F. Bay Area	18	Up 15%	Up 10%	Down 12%
Sacramento Metro.	7	Up 4%	Up 4%	Up 1%
San Joaquin Valley	28	Up 4%	Down 1%	Down 3%

- *In three of the four areas, ozone levels improved significantly on both weekends and weekdays during the 1990s. In the San Joaquin Valley, however, no significant changes in ozone occurred (Table 4-2).*

Table 4-2. Changes in ozone air quality –average results for sites in each region based on ozone data for 1992-1994 versus 1996-1998.

Region	Sites Used	Friday	Saturday	Sunday	Monday
South Coast	18	Down 25%*	Down 25%	Down 16%	Down 22%
S.F. Bay Area	18	Down 18%	Down 18%	Down 8%	Down 7%
Sacramento	7	Down 11%	Down 15%	Down 7%	Down 6%

San Joaquin Valley	22	No Change	No Change	Up 2%	Up 2%

* Percent of the 1992-1994 baseline value

Finding #2: The ozone weekend effect is not static, but changes with time

Results from the analysis of ozone from 1990 to 1998 in the South Coast Air Basin, the San Francisco Bay Area, and the Sacramento Area found:

- *In all three areas, a "Sunday effect" emerged; average ozone on Sunday in each region shifted from less than Saturday in the early 1990s to greater than Saturday in the late 1990s. The shift was about 10 percent of the Saturday ozone value in all three areas.*

- *In all three areas, the "Saturday effect" continued, with average Saturday ozone being greater than Friday. In contrast to the large shift in the Sunday effect, the Saturday effect was almost unchanged.*

Long-term trends from 1980 to 1998 for 17 locations in the South Coast Air Basin found:

- *Ozone air quality improved throughout the basin.*

- *Different parts of the South Coast Air Basin improved at different rates (Table 4-3).*

- *Weekdays improved faster than weekends (Table 4-3).*

Table 4-3. Improvements in ozone air quality* on weekdays and weekends in different sub-regions of the SoCAB (1980-82 vs.1996-98 means)

Sub-Region	Sites Used	Weekdays**	Weekends**	Difference***
All sites	17	Down 46 %	Down 33 %	13 points
Southwest L.A. County	4	Down 46 %	Down 34 %	12 points
San Gabriel Valley	3	Down 55 %	Down 36 %	19 points
San Fernando Valley	2	Down 49 %	Down 43 %	6 points
Orange County	3	Down 43 %	Down 26 %	17 points
San Bernardino/Riverside	5	Down 42 %	Down 31 %	11 points

* Regional means of annual site means of the 2^{nd}-11^{th} highest daily maximum 1-hour concentrations

** Percent of respective 1980-82 baseline values.

*** Difference of the weekday and weekend rates in terms of percentage "points".

Extending trends back to the 1970s showed:

- *In the 1970s, ozone in the South Coast Air Basin was highest on Sunday only at coastal sites, but ozone is now highest on Sunday throughout the basin.*

Finding #3: The ozone weekend effect tends to diminish at downwind locations

Results from the analysis of ozone during the 1990s in the South Coast Air Basin, the San Francisco Bay Area, and the Sacramento Area found:

- *In regions with significant weekend effects, the weekend effects tend to be greater in urban centers and smaller at downwind receptors. The downwind receptors tend to have the highest regional ozone concentrations.*

- *In the South Coast Air Basin, Sunday ozone averaged 35% higher than Friday in the urban core but only 13% higher at Santa Clarita and Lake Gregory. These sites are "downwind" receptors at higher elevation than most sites in the basin.*

- *In the S.F. Bay Area Air Basin, ozone concentrations on Sunday averaged 30% higher than on Friday in the urban core but only 14% higher at Bethel Island, Fairfield, Gilroy, and Livermore. These sites are downwind receptors that experience relatively high ozone concentrations, but they are not at high elevation.*

Finding #4: The ozone weekend effect in the South Coast Air Basin is smaller on days with high ozone-forming potential (based on meteorological conditions) compared to days when ozone-formation potential is moderate

Some days have meteorological conditions conducive to high ozone concentrations while other days do not. In the South Coast Air Basin, days with high barometric pressure and high surface temperatures tend to have high ozone concentrations somewhere in the basin.

A statistical model was developed to relate the highest ozone concentration in the basin on a given day to selected meteorological parameters for the same day. Based on data from 1992 through 1994, this model was calibrated to produce "meteorologically standardized" ozone concentrations. Days with meteorological data that produce similar met-standardized ozone values are considered to have similar ozone-forming potential. Weekdays and weekend days with high and with moderate ozone-forming potential were compared to each other.

- *The average maximum ozone on days with "moderate" ozone-forming potential was approximately 120 ppb in 1996.*

- *The average maximum ozone on days with "high" ozone-forming potential was approximately 150 ppb in 1996.*

Based on data from 1992-1994:

- *Saturday ozone was greater than Friday ozone by 9 ppb when ozone forming potential was high but 29 ppb greater when ozone forming potential was moderate.*

- *Weekend average ozone was greater than weekday average ozone by 9 ppb when ozone forming potential was high but 23 ppb greater when ozone forming potential was moderate.*

Based on data from 1996-1998:

- *Saturday ozone was greater than Friday ozone by 16 ppb when ozone forming potential was high but 21 ppb greater when ozone forming potential was moderate.*

- *Weekend average ozone was greater than weekday average ozone by 12 ppb when ozone forming potential was high but 18 ppb greater when ozone forming potential was moderate.*

During both 1992-1994 and 1996-1998:

- *Weekend ozone was about the same as Thursday (the weekday with the highest ozone) when ozone forming potential was high, but weekend ozone was substantially higher than Thursday ozone when ozone-forming potential was moderate.*

Finding #5: With the exception of Saturday afternoon, concentrations of CO and NO_X tend to be lower on weekends compared to weekdays

An analysis of CO and NO_X in eleven sub-regions of Los Angeles and Orange Counties found:

- *Concentrations of both CO and NO_X are lowest on Sunday mornings. Though higher than Sunday, Saturday morning concentrations of CO and NO_X are lower than on weekday mornings.*

- *Concentrations of CO on weekend afternoons, particularly Saturday afternoons, approach the concentrations observed on weekdays.*

- *Concentrations of NO_X on weekend afternoons, particularly Saturday afternoons, approach the concentrations observed on weekdays.*

Finding #6: Concentrations of particulate matter have improved during the last decade and tend to be lower on weekends compared to weekdays

Analyses of PM concentrations for all, or part of, 10 years (1989 – 1998) show:

- *From 1988-90 to 1997-99, a marked decrease in exceedances of the California 24-hour PM_{10} standard occurred in the South Coast Air Basin (-85%), San Francisco Bay Area Air Basin (-69%), San Joaquin Valley Air Basin (-68%), and Sacramento Valley Air Basin (-50%).*

- *The most abundant measured components of PM_{10} and $PM_{2.5}$ in the SoCAB are ammonium, nitrate, sulfate, and elemental carbon.*

- *Nitrate is the largest single chemical component of PM_{10} (23-26%) and $PM_{2.5}$ (28-40%) in terms of mass in the SoCAB.*

- *SSI samplers reported the lowest average PM_{10} on Sundays at 16 of 17 locations in the SoCAB.*

- *Dichot samplers reported the lowest average $PM_{2.5}$ on Sundays at 6 of 9 locations.*

- *Summer PM_{10} concentrations from a TEOM sampler at Azusa averaged 23% lower on Sundays and 19% lower on Saturdays compared to the weekdays, which averaged approximately 62 $\mu g/m^3$.*

- *Air quality data for the SoCAB indicate that average PM_{10}-nitrate concentrations decreased substantially on weekend days and on most weekdays from 1988-1991 to 1997-1999.*

- *Air quality data for 1997-1999 in the SoCAB indicate that weekend average concentrations of PM_{10}-nitrate were lower than the weekday average at 14 of 15 locations. Across the basin, the average for PM_{10}-nitrate on weekend days was 13% lower than the average for weekdays.*

- *Some day-of-week comparisons of particulate matter concentrations are difficult to interpret. For example, measured PM_{10}-nitrates in the SoCAB can be lowest on a mid-week day in some locations. No simple explanation in terms of source strengths, atmospheric chemistry, or meteorology is readily available. It is possible that the data include influences related to schedules for sampling and laboratory analysis (e.g., artifacts).*

- *In the San Francisco Bay Area, PM_{10} from SSI samplers was lowest on Sunday, followed by Wednesday, and then Saturday. However, these differences did not achieve statistical "significance".*

Finding #7: Concentrations of seven toxic air contaminants are lower or the same on weekends compared to weekdays

Analyses of toxic air contaminant (TAC) concentrations in the SoCAB show:

- *Between 1990 and 1997, the annual average concentration of benzene, a human carcinogen, declined by 70% or more based on data for five sites in the SoCAB. The comparable decline in the annual average concentration of 1,3-butadiene was 40% or more.*

- *Concentrations of three TACs – benzene; 1,3-butadiene; and perchloroethylene – are notably lower on weekends compared to weekdays. Benzene and 1,3-butadiene are directly emitted pollutants, primarily from motor vehicles. Measured concentrations of these compounds correlate well with observed reductions in motor vehicle traffic on weekends.*

- *Although the concentrations of some TACs were similar on all days of the week, no TAC demonstrated that higher concentrations should be expected on weekends compared to weekdays.*

4.2 Objective #2 – Examine the potential causes of the weekend effect

Finding #8: Ozone and other pollutants carry over aloft and can affect ground level concentrations on the following day

Measurements of pollutants aloft are very limited but some useful findings follow from selected field studies.

A surface-based ozone LIDAR instrument was installed at El Monte and operated during the intensive operational periods (IOPs) of the SCOS97 field study.

Pollutants aloft (e.g., O_3, NO_Y, NO_X, VOCs) were also measured periodically during the IOPs of SCOS97 using aircraft and balloon-borne instruments.

Results of these measurement programs reveal the following:

- *Significant layers of polluted air aloft may be the norm rather than the exception in the South Coast Air Basin, particularly on days with meteorological conditions that favor high ozone concentrations.*

- *Significant layers of polluted air aloft may persist for more than one day.*

- *Layers of polluted air aloft can be more than 1000 meters thick and can begin less than 200 meters above the surface.*

- *Layers of polluted air aloft harbor 60 to 140 ppb or more of ozone in addition to ozone precursors.*

- *Layers of polluted air aloft mix with air near the surface as the mixing layer increases in depth between sunrise and mid- afternoon.*

- *Pollutants that carryover aloft may generate new ozone following sunrise and before fresh emissions mix upwards from the surface.*

Finding #9: Extra traffic on Friday and Saturday nights may inject additional ozone precursors into the air near ground level, but current air quality measurements do not indicate a significant impact of these emissions on ground level concentrations the following day

- *Traffic volumes are significantly higher on Friday and Saturday nights compared to other nights of the week. The increase is probably limited to light-duty vehicles.*

- *Emissions from greater traffic volumes on Friday and Saturday nights almost certainly are trapped in a layer of air near the ground that forms as the Earth's surface cools.*

- *Emissions of ozone precursors from the increased traffic on Friday and Saturday nights presumably also increase at this time and may carry over to the next day near the surface.*

  Measured concentrations of CO, VOCs, and NO_X at sunrise on Saturday and Sunday mornings are lower than the weekday concentrations at the corresponding hours despite the presumed carryover of additional emissions at the surface on weekends.

  Therefore, ozone precursors that carryover under the surface-based inversion on Friday and Saturday nights <u>do not appear to be a significant cause</u> of the ozone weekend effect.

Finding #10: Some changes from 1994 to 1998 in the hourly patterns of ozone by day-of-week may reflect changes in hydrocarbon (VOC) emissions in the SoCAB

- *Ozone concentrations at many sites in the air basin tended to peak a little later in the day in 1998 than in 1994. This pattern is consistent with less reactive VOC emissions with little change in VOC/NO_X ratios.*

Finding #11: Concentrations of CO (surrogate for VOCs) and NO_X declined along with ozone during the 1990s

Changes in CO were used as a partial surrogate for changes in VOCs or hydrocarbons. This was done because VOC or HC data are not available at most air quality monitoring locations. Analyses of data for CO and NO_X by day-of-week in the 1990s found:

- *Concentrations of CO and NO_X in the SoCAB declined from 1994 to 1998.*
- *Declines in CO were similar on weekdays and weekends from 1994 to 1998.*
- *Declines in NO_X were similar on weekdays and weekends from 1994 to 1998.*
- *A similar analysis based on direct measurements of VOCs was not possible due to limited data.*

Finding #12: VOC/NO_X ratios are greater on weekends than weekdays

- *Averaging all days with data, VOC/NO_X ratios calculated using TNMOC from PAMS data range between 4.0 and 9.0 ppmC/ppm. Depending on the VOC reactivity, these numbers indicate that ozone-forming chemistry in the SoCAB may be VOC-limited, at least near ground level.*
- *On weekends, VOC/NO_X ratios tend to be 10% to 20% higher on Saturdays and 20 to 40% higher on Sundays compared to the weekday ratios at the same location and for the same period of the day.*
- *Recent research indicates that actual VOC concentrations average 30% greater than the measured "sum of VOC" species used to compute many VOC/NO_X ratios. This would result in actual VOC/NO_X ratios that are also 30% or more greater than calculated ratios on all days of the week. This would tend to move ratios toward the most efficient ozone production regime.*
- *The routine NO_X measurements reported by sampling instruments include several nitrogen compounds in addition to NO and NO_2. The composition of this NO_X measurement changes from weekdays to weekends. If based on artifact-free NO_X measurements, ambient VOC/NO_X ratios would be greater than currently indicated.*

Finding #13: Ozone-forming photochemistry appears to be more active on weekends compared to weekdays

Analysis of surface data for VOCs and nitrogen oxides in the SoCAB indicate that photochemistry creates more ozone on weekends compared to weekdays. The data indicate:

- *Given the uncertainties in VOC, NO_X, and NO_2 measurements, VOC/NO_X ratios are commonly between 4.0 and 9.0 ppmC/ppm.*

- *VOC/NO_X ratios are about 10% to 20% greater on Saturdays and 20% to 40% greater on Sundays compared to weekdays.*

- *The NO_2/NO ratio is higher for almost all daylight hours on Sunday and Saturday compared to weekdays at almost all locations.*

- *Although NO_2 concentrations are typically lowest on Sundays, the NO_2/NO ratio is highest on Sundays because NO concentrations typically decline proportionally more than NO_2 concentrations decline (perhaps due to a higher level of photochemical activity - higher VOC/NO_X ratio and proportionately greater O_3 oxidizes NO emissions to NO_2 faster).*

Finding #14: Reactivity of VOCs appears to be lower on weekends compared to weekdays

- *PAMS data indicate possible differences in the VOC composition on weekends compared to weekdays. Some data indicate that reactive compounds are a smaller fraction of the VOC mix on weekends. Reactive compounds tend to be oxidized more quickly than less reactive compounds, which persist longer in the atmosphere. Therefore, these data indicate that the VOC mix on weekends may contain a larger fraction composed of pollutants that persist in the air ("carryover"). If so, the effect of carryover would be greater on weekends compared to weekdays.*

- *A special sampling program in the summers of 1995 and 1996 indicated that the ozone-forming potential (incremental reactivity) of the ambient VOC mixture dropped between 1995 and 1996. This change in the ambient air is consistent with the expected effect of reformulated gasoline.*

- *Data from the special sampling program also indicate that the incremental reactivity of the ambient VOC mixture is slightly lower on the weekends than on weekdays.*

- *Differences in the incremental reactivity on weekends versus weekdays appear to be greater in the afternoon than in the morning (i.e., afternoon reactivity is lower on weekends than on weekdays).*

Finding #15: Daily and hourly traffic counts of heavy-duty and non-heavy-duty vehicles on freeways in the SoCAB vary by day of week

Although not necessarily representative of total traffic activity in the SoCAB, analyses of daily and hourly freeway traffic counts from CALTRANS' Weigh-in-Motion (WIM) stations on freeways in and around the South Coast Air Basin show the following:

- *In the SoCAB as a whole, the total daily traffic volume on freeways is lower on weekends compared to weekdays.*

- *Daily traffic volumes of heavy-duty vehicles (on freeways) decrease on weekends throughout the SoCAB.*

- *Daily traffic volumes of cars and other non-heavy-duty vehicles decrease on weekends in most parts of the SoCAB. On entry and exit routes and in areas with strong recreational interest, however, daily traffic volumes of non-heavy-duty traffic may increase on weekends.*

- *Because heavy-duty traffic decreases proportionately more than non-heavy-duty traffic on weekends, the ratio of heavy-duty to non-heavy-duty vehicles is substantially lower on weekends compared to weekdays. Estimated proportions of heavy-duty vehicles are 1:20 on weekdays, 1:50 on Saturday, and 1:100 on Sunday.*

- *Among weekdays, Friday had the highest volume of non-heavy-duty traffic at all sites but one. The increase on Friday relative to the mid-week volume was 7% for all sites together.*

- *At almost all locations, hourly volumes for non-heavy-duty and heavy-duty traffic differ greatly on weekdays. Non-heavy-duty traffic exhibits high volumes during both morning and evening "rush hours," whereas heavy-duty traffic increases continuously to a maximum for the mid-day hours and declines again before the afternoon rush hour.*

- *At almost all locations, hourly volumes for heavy-duty traffic on weekends differ greatly from the weekday volumes. The weekend volumes are substantially lower, especially on Sunday, throughout the day compared to weekday volumes.*

Finding #16: In Los Angeles and Orange Counties, hourly traffic counts on freeways vary by day of week

Although not necessarily representative of travel on surface streets, analyses of hourly freeway traffic counts from hundreds of real-time "loop detectors" on freeways in eleven sub-regions of Los Angeles and Orange counties show the following:

- *Despite sub-regional differences, hourly traffic volumes by day-of-week have similar general characteristics throughout Los Angeles and Orange Counties.*

- *The total volume of traffic is substantially different on weekends compared to weekdays in all 11 sub-regions. Saturday and Sunday traffic totals are approximately 89% and 78% of weekday totals.*

- *Saturday traffic volumes are smaller than weekday volumes during the morning and evening commute periods, but equal to or greater than weekday volumes at other times of the day.*

- *Sunday traffic volumes are lower than all other days between 5 a.m. and 8 p.m. except for a few mid-day hours in some sub-regions when Sunday volumes reach weekday levels.*

- *In all 11 sub-regions on Friday and Saturday nights, between 10 p.m. and 4 a.m., the hourly traffic volumes are 10% to 100% greater than all other nights in the week.*

- *The timing of traffic is dramatically different on weekends compared to weekdays in all 11 sub-regions.*

- *Distinctive "rush-hour" increases in morning and evening traffic during the commute periods occur on weekdays but not on weekends. From 6 a.m. to 8 a.m., Saturday volumes are approximately 40-50% of mid-week volumes and Sunday volumes are approximately 20-30% of mid-week volumes.*

- *The timing of traffic on weekdays and weekends correlates well with observed hourly concentrations of CO and NO_X. Both of these pollutants come primarily from motor vehicles.*

4.3 Objective #3 – Identify the plausible factors/causes of the weekend effect

Finding #17: The available data are sufficient to identify and quantify the ozone weekend effect, but the data are not sufficient to determine its cause or causes.

Although many interesting findings emerged from the analyses in this report, the cause or causes of the ozone weekend effect could not be determined. Multiple hypotheses are plausible and the data needed to separate and quantify their effects individually are not available. Although the work performed by the Weekend Effect Working Group has gone a long way toward establishing the plausibility and likely significance of the various weekend effect hypotheses, significant uncertainties

remain due to the limited nature of the available data (e.g., conditions aloft, accurate VOC and NO_X measurements). Recommendations are included in the report to collect sufficient quantities of the appropriate data for addressing the causes of the weekend effect.

4.4 Objective #4 – Evaluate control strategy implications from the weekend effect

After investigating the ozone weekend effect, reviewing the historical trends of air quality and emissions, and considering the health and environmental impacts, staff believes that no change is currently warranted in CARB's strategy of reducing both precursors of ozone (VOC and NO_X) in an expeditious manner.

Finding #18: Ozone air quality has improved dramatically while NO_X controls have been in place.

During the 1980s and 1990s when NO_X emission reductions were actively pursued, various indicators of ozone air quality in the South Coast Air Basin declined dramatically (e.g., peak concentrations cut by 25% in the '80s and 37% in the '90s; exceedances of CAAQS cut by 9% in the '80s and 40% in the '90s; exceedances of NAAQS cut by 14% in the '80s and 67% in the '90s; Stage I Episodes declined about 50 days per year in each decade - by 46% in the '80s and 100% (i.e., eliminated) in the '90s). Although the monitoring methods have changed, there has been no obvious detriment to ozone air quality or the rate of improvement since NO_X reductions were pursued in addition to ROG reductions. In fact, the greatest improvement has occurred during the 1990s when NO_X emissions were rapidly decreasing. Ozone concentrations continue to decline on weekends, although at a slower rate than on weekdays.

Finding #19: Exceedances of the NAAQS in the SoCAB are now limited to weekends.

The highest ozone concentrations in the SoCAB now occur on the weekend, most frequently on Sunday. Weekend ozone values now define the "design value" for ozone air quality planning. In other words, weekend ozone levels now serve as the basis for designing emission reductions that will bring the area into compliance with state and federal ambient air quality standards. This situation has created a critical need for day-of-week emission inventories for input to the photochemical modeling applications that are used to design and document the sufficiency of control plans. Now that the peak ozone concentrations occur on the weekend, it is even more important that the salient features of the atmospheric processes involved in the ozone weekend effect are understood and quantified.

Finding #20: Significant uncertainties remain as to the relevance of the cause(s) of the ozone weekend effect to long-term control strategies.

Because of the dual nature of NO_X emissions on ozone air quality, the different hypotheses may have different NO_X control implications. Because of the relatively short life-time of NO_X in the atmosphere, some scientists advocate that the weekend effect has direct relevance to long-term control strategies. Staff believes that significant uncertainties remain as to the relevance of the weekend effect to control strategies and are not convinced at this point that CARB should change its highly successful ozone control strategy of reducing NO_X emissions in addition to VOC emissions. Important differences between processes during the weekend transition and long-term control measures include:

1) NO_X is reduced much more than VOC on the weekend but historical reductions of VOC have been much greater than reductions of NO_X. The difference though in the reduction of precursors has been shrinking and the reductions are projected to be comparable in the '00s. Thus, the relative reduction of precursors is drastically different on weekends than has been or will be with control strategies.

2) The bulk of the ozone precursor emissions comes from on-road motor vehicles. However, the temporal distribution pattern shifts from bi-modal peaks associated with traffic commute periods on weekdays to a uni-modal peak at mid-day on weekends.

3) Similarly, the trip ends are likely different from weekdays to weekends with a shift in emissions from the urbanized areas to the suburban areas.

4) The influence of heavy-duty diesel vehicles is greatly reduced on weekends but would not be under a typical emission reduction program.

5) The air quality occurs in the context of conditions during the previous hours and days. The weekend effect occurs after a potential build-up of pollutants during the work week and extra motor vehicle activity on Friday and Saturday evenings followed by greatly reduced activity on weekend mornings. Furthermore, much of the ozone and precursor carryover and additional ozone formation occurs aloft, above what is typically seen by the traditional surface-based monitoring network. The interaction of the air quality aloft with variable amounts and timing of fresh emissions has an unknown effect at this time but would be a perturbation of across the board (temporal and spatial) reductions associated with control plans.